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WEIGHT ANALYSIS

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Weight Analysis

XV-5A Lift Fan
Flight Research Aircraft Program

November 1963

ADVANCED ENGINE AND TECHNOLOGY DEPARTMENT
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Aircraft weight is of prime consideration in V/STOL aircraft design. The principal aircraft performance parameters of range, endurance, and payload bear directly on the empty weight. This is particularly true with vertical takeoff aircraft since the maximum gross weight is usually limited by the lifting capabilities of the specific propulsion system and design.

Throughout the engineering design and manufacturing phases of the XV-5A considerable effort and stringent means of control were applied to monitor and manage the weight status of the aircraft. Aircraft weight was controlled by:

1. A digital computer system was established which reflects both target weight and current weight of all items weighing one half pound or more. Group allocation provides for those items under one-half pound. Ready reference to the current weight of each item is provided by the digital run and allows a basis for comparison to the target weight. The data runs are revised every two weeks keeping all design personnel current on the weight factors concerning their area of responsibility. Additional features of the digital program provided detailed analyses of mass and inertia distributions as well as the weight status. Current weights and inertias were continually fed to the loads, flutter, and stress groups so that corrective action could be taken against any undesirable weight trends as the design progresses.

2. Design analyses were performed on vendor purchased components to obtain reliable operation at minimum weight. Consultation with the vendors' engineering groups yielded weight reductions that would have normally been missed.

3. Task force teams, organized of design specialists, were utilized to perform audits on both the structural design as well as the various aircraft systems to evaluate weight reduction methods. Examples of the results of these audits include the thrust spoiler which has been completely redesigned to reduce weight

plus an evaluation of the flap actuation system comparing hydraulic actuation devices with electrical types.

As the program and detail designs progressed, it became evident that considerable problems existed which were unknown at the program beginning. As each of these problems came up, serious considerations were given to the possible solutions, aircraft total performance objectives, and the usually attendant weight penalty. In almost every case, the affect on the operational usage of the aircraft was the prime consideration for the problem solution. Personnel safety, aircraft reliability, aircraft flying qualities and program design objective were the major judgment factors. Examples of these problem areas which affected weight are listed below.

WEIGHT ADDITIONS:

1. Wing Fan Doors

   Closures for the upper wing surface were initially envisioned as an articulated louver inlet system. Various studies on the imposed flight drag, complexity of actuating mechanism, and fan performance losses, led to the design of the cantilevered butterfly style door closure. Scale model tests indicated less than 1% hover lift loss for the butterfly doors while losses as high as 5.5% were seen with the articulated vanes. Full scale model testing at Ames on the butterfly closures indicated no measurable changes in lift, drag, or moments during cross flow velocities. The weight of the closure system has increased by 42 pounds, primarily due to stiffening required after the initial structural test. However, the negligible performance effects and actuation simplicity warrant this style of closure.

2. Two-Position Landing Gear

   The original design as submitted did not include a two position feature for the main landing gear. Testing proved that in order to achieve maximum static lift and acceptable low conventional rotation speed at take-off, a two position feature was required. Model tests indi-

2. (Cont'd)

cated a 2.5% gain in static lift when the main gear was moved aft, out of the fan efflux, while an estimated 100 pounds tail weight increase would have been necessary to achieve an acceptable low rotational speed with the landing gear in the aft position. A weight increase of approximately 40 pounds is chargeable for this two position feature; however, there are several additional advantages. The aft movement of the gear should reduce the hot gas impingement during VTOL, and greater research flexibility should be possible with this pilot-controlled gear position feature. It is expected that a two position gear will not be required operationally.

3. <u>Aileron Droop</u>

Wind tunnel testing indicated that the original estimate of maximum C_L was optimistic, partly because the flap increment suffered due to fan flow interference. Various devices were studied to increase C_L, such as leading edge flaps and slots, but were discarded because of the necessary higher angle of attack and consequent reduced fan horizontal performance. In order to obtain good low speed handling qualities and a higher transitional speed, drooped ailerons with power boost control were added for a 10% lift increase, based on model tests, but at a weight increase of approximately 19 pounds.

4. <u>Principal Axis</u>

Detail analysis of the original aircraft configuration indicated that the principal axis was declining at 8 1/2 degrees from the aerodynamic axis. The effect of this problem was that at high flight speeds a coupling was indicated between roll and yaw, such that the aircraft would require full autostabilization in conventional flight. The fuselage was configurated from the results of parametric analysis resulting in an acceptable angle of 3 1/2 degrees. The estimated associated weight increase is 30 pounds; however, the decreased roll-yaw coupling should enable the aircraft to be flown without stability augmentation in high speed flight in accordance with the original design intent.

5. Ejection Seat Structural Provisions

In order to provide maximum pilot safety throughout the XV-5A flight map the cockpit area was structurally strengthened to receive the higher weight and impulse of the North American LW-2 ejection seat. The weight increase of 18 pounds, besides providing for the LW-2 seat should be sufficient to allow installation of the Douglas seat as well. An additional 63 pounds has been included into the aircraft weight accounting for the increased LW-2 seat over the originally planned LW-1 seat.

6. Thrust Spoiler

During the detail design of the thrust spoiler a 26 pound weight increase over the estimated weight resulted in order to achieve the desired degree of thrust attenuation. It is expected that dive brakes rather than thrust spoilers will be utilized on operational aircraft.

7. Aerodynamic Loads

The high speed, low altitude requirement of 500 knots, which develops a dynamic pressure of 850 pounds per square foot resulted in severe bending loads in the fuselage, due in part to the flat areas required to accomodate the side-by-side seating feature. Extensive wind tunnel aerodynamic and flutter model testing indicated these structural loads as well as other longitudinal and lateral stability problems. Specific areas that were redesigned as a result of these tests were structural beef-up of the forward and aft fuselage, increased stiffness in the vertical fin, increased span of the longitudinal tail, plus a wing tip dihedral change. The total weight increase associated with these re-configurations is estimated at 85 pounds.

8. Electrical Wiring

As a result of the structural load weight increases, the aircraft battery plus inverters were moved to the aft equipment compartment in order to maintain the aircraft center of gravity within the limits for both conventional flight and hovering trim considerations. To accomodate the

8. (Cont'd)

relocation of these electrical components, longer wire runs became necessary at a weight increase of 15 pounds.

9. Electric Mixer Box

Considerable reliability studies have been made of the aircraft conversion flight phase, which have indicated the need for proper sequencing of the various items such as diverter valves, horizontal stabilizer, fan doors, pitch fan inlet and thrust reverser doors, and wing flaps to preclude undesirable interactions. Programming and synchronizing of these items has been included into the control system design in the form of time delay relays and interlock mechanisms, but with an attendant weight increase of 13 pounds.

10. Cross Duct Mounting

Several considerations were factored into the initial detail design of the crossducts which transmit the hot J85 exhaust gases between the diverter valve and the fan scroll inlets. In order to minimize the cross duct shear loads imposed on the diverter valve and scroll and to prevent undesirable deformation of these two components, restraints were added between the cross ducts and airframe. These additional duct mounts, estimated at 48 pounds, were considered necessary from a reliability standpoint.

11. Battery

In order to meet the reliability standards that have been established for the XV-5A, a requirement exists for a battery capable of powering the emergency circuits for five minutes plus one conversion cycle. This high strength high capacity requirement was not originally anticipated because of the dual electrical generating systems. In spite of the use of a special nickel silver battery in lieu of a lead acid battery, the weight increased 12 pounds. The reliability designed into the XV-5A should be especially useful when military pilots begin to fly the aircraft.

12. Cooling Requirements

Engine driven cooling fans plus hot air aspiration into the lift fans was chosen as the means of providing cooling air throughout the XV-5A after careful consideration of several other means. Temperature data from both Ames model testing and Evendale development efforts revealed excessive conditions on several aircraft structural components from hot turbine gas impingement. This information became available at a time long past the initial design phase of the airplane and required extensive additional insulation to the fuselage and wings plus material changes in some areas. An estimated weight increase of 150 pounds has resulted.

13. Brakes

An estimated weight increase of 10 pounds has occurred in the brakes to provide longer continuous use and permit conventional landings to be conducted successfully relatively independent of braking system limitations.

14. Canopy

The canopy was redesigned from a two-beam structure to a single beam canopy to improve overhead visibility at a 20 pound weight increase. An added benefit that resulted was a clear span area for "through-the-canopy" ejection.

15. Lift Fan Overspeed Protection

During the detail analysis of the airplane/propulsion system, based upon Ames wind tunnel tests, the possiblity of fan stall and subsequent destructive overspeed near aircraft stall angles of attack was discovered. Rather than establish a severely restricted flight envelope for the airplane, an overspeed warning system and automatic throttle cutback was included in the design at an estimated weight of 18 pounds. The research nature of the aircraft warranted this protection to enable investigation of the aircraft flight envelope edges. It is not expected that this overspeed protection would be required for operational use.

16. Pitch Control Fan

The pitch fan has increased in weight from 90 pounds during contract negotiations to 109 pounds in Specification #113, to an actual weight of 113 pounds. This weight gain provided for increased control power capability from an original contract value of 1300# lift to a design goal of 1500# lift. The performance of actual hardware is 1656# lift under the same ANA 421 hot day, 2500 ft. conditions. Wind tunnel data has indicated that pitch trim control with the 1300# fan originally planned would have been marginal. The increased thrust of the pitch fan allows for more control power thus providing increased control margin in hover and low speed flights. Added flexibility of testing during the research phase should be available due to the increased performance

17. Pitch Fan Duct Diameter

A greater gas horsepower input is required to obtain the increas performance from the pitch control fan mentioned above. In order to provide this increased gas power, the duct size was increased from six inches to seven inches in diameter with a weight penalty of approximately 15 pounds. The original 1300# fan required 10.6% bleed of the total J85 engine, whereas the present 1656# fan utilizes 12.3% bleed.

18. Pitch Fan Inlet

Although an approximate weight increase of 15 pounds has developed during the design of the inlet louver system for the pitch fan, other advantages warrant the decision for this type of closure over any other. No visibility restrictions, clean aerodynamics when closed, little or no destabilizing effects on the aircraft, plus compatibility with the fuselage, all are factors for this type system.

19. Pitch Fan Thrust Modulator

The original calculated weight was based on a system of dump valves for the emission of hot gas for reverse force and inlet guide vanes for controlling positive lift. Fully modulated closure doors were chosen as

19. Cont'd)

the best means of controlling the amount and direction of thrust from the pitch fan. These thrust reversing doors are capable of producing smooth thrust variations from 100% positive to 20% negative. The range of thrust required can be obtained at nearly constant fan speed with a constant hot gas supply (no throttle movement), thus reducing the number of valves required. Development timing, performance uncertainties, and hot gas discharge effects are all greatly reduced by this approach. The estimated weight increase over non-modulated door and actuators is 36 pounds.

WEIGHT REDUCTION:

In addition to the great amount of effort that was expended in parametric studies, material development and process development to keep the weight increases to a minimum compatible with the goals for the aircraft use, many items of weight reductions were incorporated into the airplane. Several of these items are listed below:

1. Lift Fans

Through conscientious design methods, the main lift fan weight has been reduced by 105 pounds for the complete system of two fans. This weight reduction combined with the increased performance achieved by the fans, a system increase of 1000 pounds over specification lift, presents increased airplane capabilities in terms of:

a) A higher gross weight can be carried.

b) Increased control power is available at design gross weight giving increased flying reliability during the critical hover conditions.

c) Increased range through both increased fuel load capability and lower power settings required for constant weight.

d) Increased vector performance which affords greater fan powered acceleration for the aircraft and possibly higher maximum fan powered flight speeds.

2. PCM Data Acquisition System

A transistorized data acquisition system was custom designed to meet the XV-5A requirements. The low weight of 100 pounds for the system enables a wide variety and weight of data pickups to be installed within the total weight allowable for instrumentation.

3. Generators

Brushless generators were custom designed for the XV-5A to save 22 pounds over the weight for standard brush-type generators.

4. Space Frame

An extensive process development program enabled the use of high strength mar-aged steel in lieu of 4130 steel. Estimated weight saving is approximately 40 pounds.

5. Taper Skins

Extensive use has been made of the chem-milling process and conventional milling in order to taper skins to thicknesses commensurate with the loads they carry. Attention to minute detail, even in access doors, has saved many pounds in the aircraft. Typical are the wing skins where an estimated 20 pounds was saved through tapering.

6. Inverters

Use of static inverters in lieu of conventional rotary inverters saved approximately 5 pounds.

7. Boost Pumps

Use of engine bleed/air driven fuel boost pumps instead of electrically driven pumps saved 6 pounds.

8. Hydraulic System

Use of a combination reservoir and accumulator (Resicume) in lieu of two separate items saved 8 pounds.

9. Magnesium Skins

Magnesium material in place of aluminum was used in various areas of the forward and aft fuselage as well as at the vertical stabilizer for a weight savings of approximately 30 pounds.

10. Titanium Bolts

Titanium bolts were used throughout the aircraft for a 12 pound weight savings.

11. Engine Firewalls

Comprehensive design effort on the firewalls between the J85 engine and the aircraft structure resulted in a 6 pound weight reduction.

12. Engine Cowl

The engine cowl was designed and fabricated utilizing aluminum honeycomb which saved approximately 30 pounds over conventional skin - frame aircraft construction.

PERFORMANCE EFFECTS:

The effect of the increased aircraft empty weight can be seen in Figures 1 through 4. In Figure 1, the VTOL take-off endurance,, and Figure 2, the conventional take-off endurance, it can be seen that with the present aircraft weight, endurance is reduced by 19 minutes or 65 nautical miles of range at a common 9200 pounds gross weight. This is not a complete evaluation however, since the propulsion system has demonstrated an increased lift capability of approximately 1000 pounds beyond the original specification values. This additional lift has been included in the VTOL endurance shown in Figure 1. At lift to weight ratios of 1.05 and 1.2, the following endurance times are possible:

ENDURANCE TIMES

	Design Objectives	Present Values
L/W = 1.05	45 Minutes	61.5 Minutes
L/W = 1.2	20 "	21.5 "
at 9000 pounds GW	45 '	25 '

As can be seen above, the design objectives for these lift to weight ratios can be met, with the exception that at 9200 pounds GW only 25 minutes will be possible rather than the 45 minutes objective.

Increased empty weight will also affect the permissible load factor. Figure 3 depicts the change in load factor for a 9900 pound aircraft over the design weight of 9200#. A load factor of 3.72 rather than 4.0 will exist for this 9900 pound aircraft, which can perform the necessary 45 minute mission objective.

Figure 4 indicates the predicted forward speed in the fan powered mode as a ratio of aircraft stall speed with increasing aircraft gross weights. From this data, transition flights up to 1.2 V stall should be possible under standard day sea level conditions but not at 9200# hot day altitude

CONCLUSION:

Aircraft weight increased during the design and manufacturing of the XV-5A, in spite of the close surveillance and careful consideration of the principal program objectives and the best way to meet the needs of the Army. The overweight estimate of 335 pounds becomes secondary when the additional system lift (1000 pounds) is considered. At reduced load factor 3.72 rather than 4.0, the endurance times under VTOL conditions are predicted to be in accordance with the specification.

TABLE I

WEIGHT SUMMARY

Weight Increases	LBS.	Weight Reductions	LBS.
Wing Fan Doors	42	Lift Fans	105
Two Position Landing Gear	40	Generators	22
Aileron Droop	19	Space Frame	40
Principal Axis	30	Taper Skins	20
Electrical Wiring	15	Inverters	5
Ejection Seat Provisions	18	Boost Pumps	6
LW-2 Seat Increase	63	Hydraulic System	8
Thrust Spoiler	26	Magnesium Skins	30
Aerodynamic Loads	85	Titanium Bolts	12
Electric Mixer Box	13	Engine Firewalls	6
Cross Duct Mounting	48	Engine Cowl	30
Battery	12		
Cooling Requirements	150		
Brakes	10		
Canopy	20		
Lift Fan Overspeed	18		
Pitch Fan	23		
Pitch Fan Ducts	15		
Pitch Fan Inlet	15		
Pitch Fan Thrust Modulator	36		
Total Increase	698	Total Reduction	284

Present estimate of aircraft empty weight = 7574 lbs.
Presently contracted weight 7161.5
413.5 lbs.

Of this weight difference, 78.5 pounds should not be changeable to the aircraft (15# for ejection seat interchangeability, and 63.5# for LW-2 increase) thus the true overweight is 413.5 - 78.5 = 335 pounds.

TAKE-OFF WEIGHT VERSUS ENDURANCE
2500 FEET ANA 421 HOT DAY
CONVENTIONAL FLIGHT ENDURANCE
FOLLOWING 5 MINUTES AT HOVER
INCLUDING 10% FUEL RESERVE

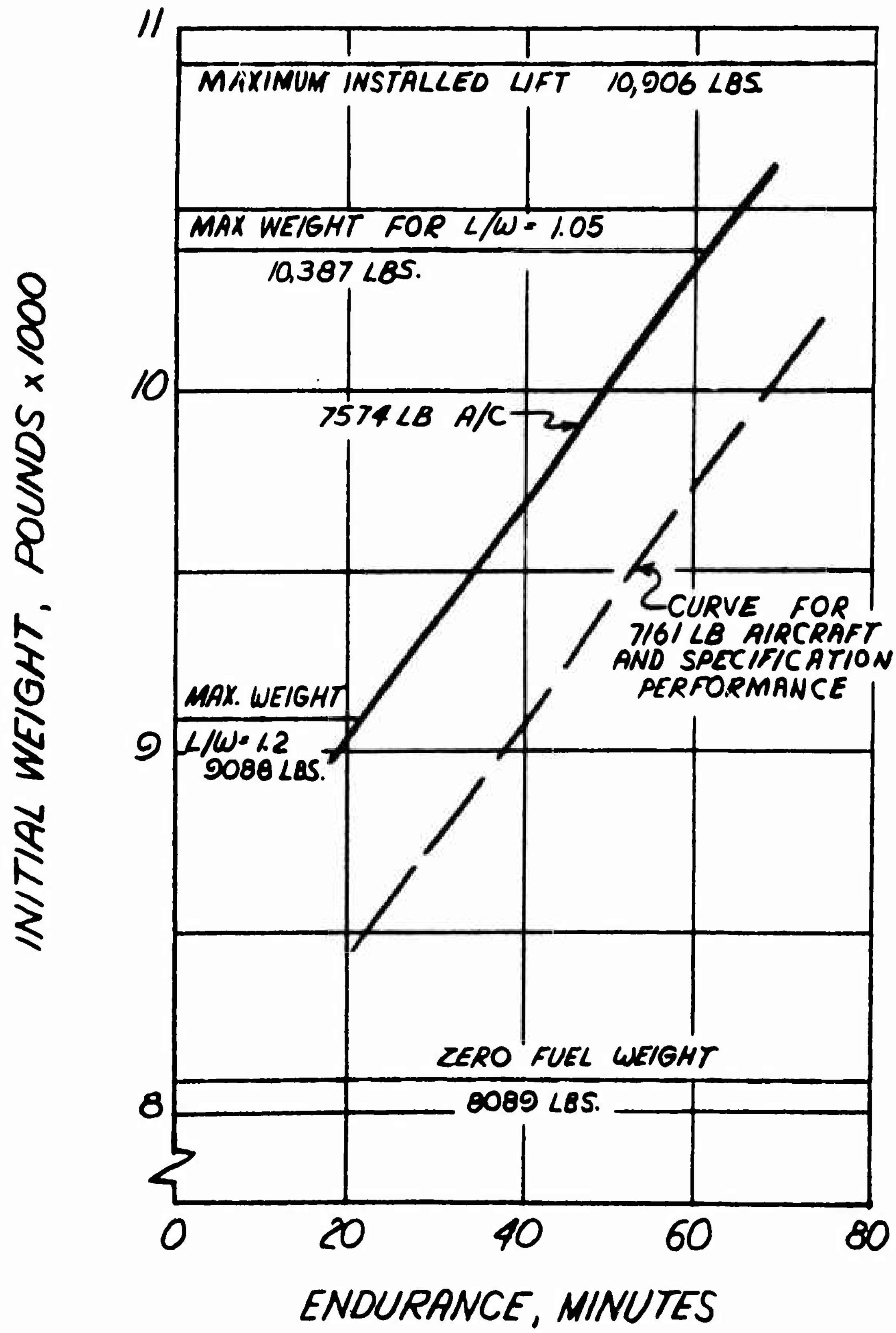

FIG 1

MAXIMUM FLIGHT ENDURANCE AND DISTANCE TRAVELED
VERSUS INITIAL WEIGHT
CONVENTIONAL TAKE-OFF AND LANDING
CRUISE ALTITUDE = 10,000 FEET
TWO ENGINES OPERATING
ARDC STANDARD DAY

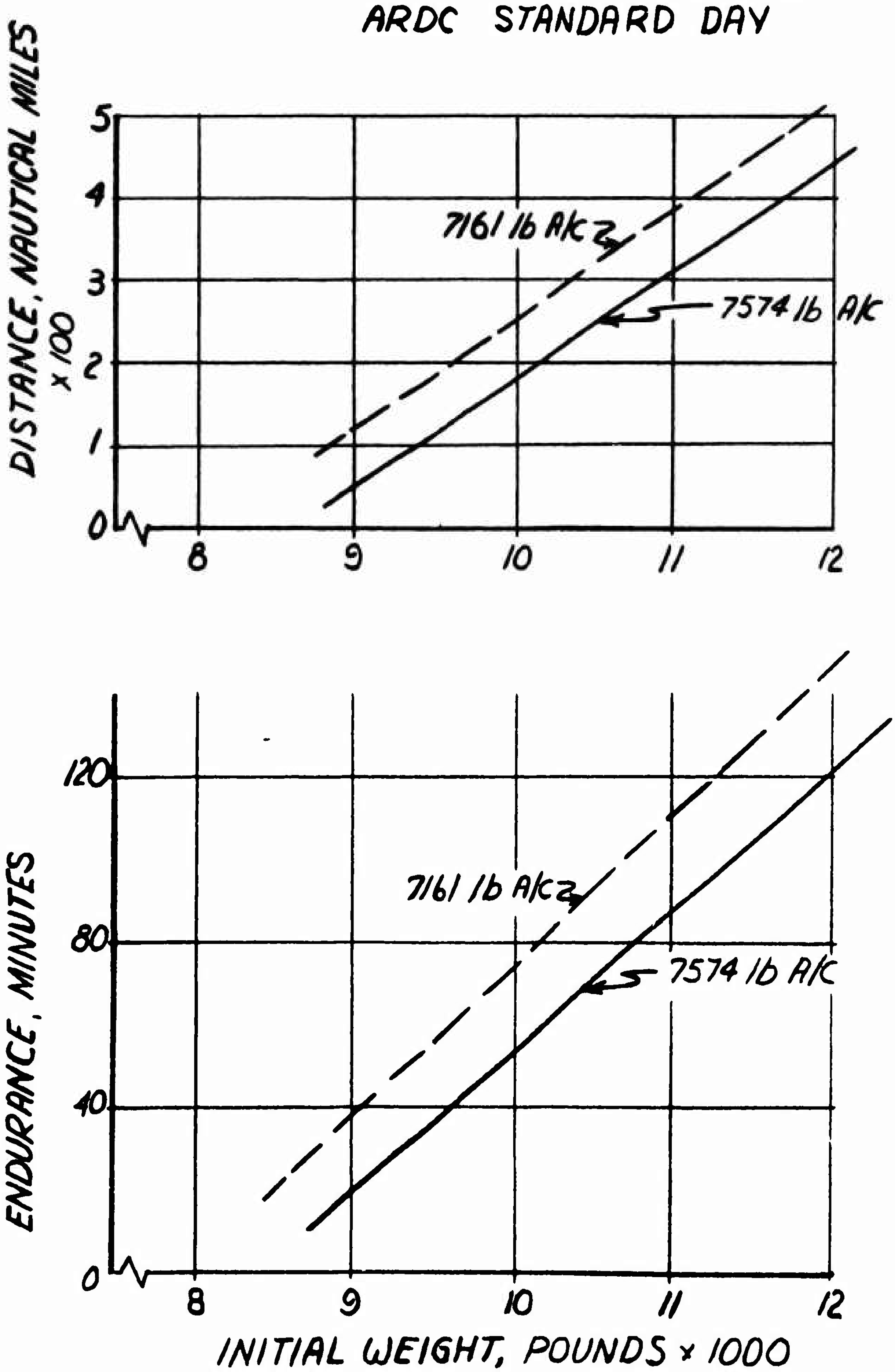

FIG 2

MANEUVERING ENVELOPE - GUST DIAGRAM

XV-5A

AT

GROSS WEIGHTS = 9200# AND 9900#

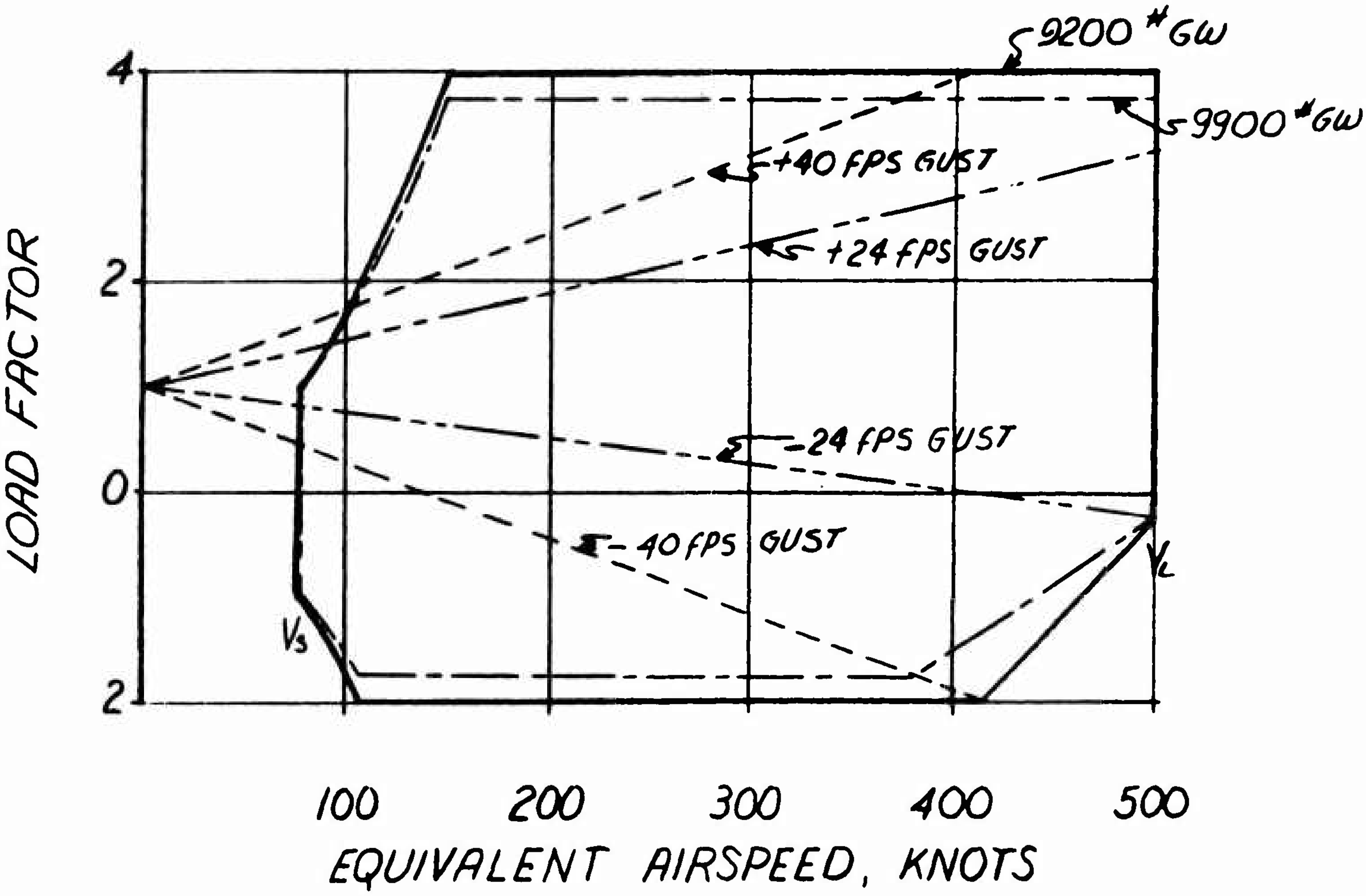

FIG 3

7/9/63
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EFFECTS OF GROSS WEIGHT ON

XV-5A TRANSITION SPEED

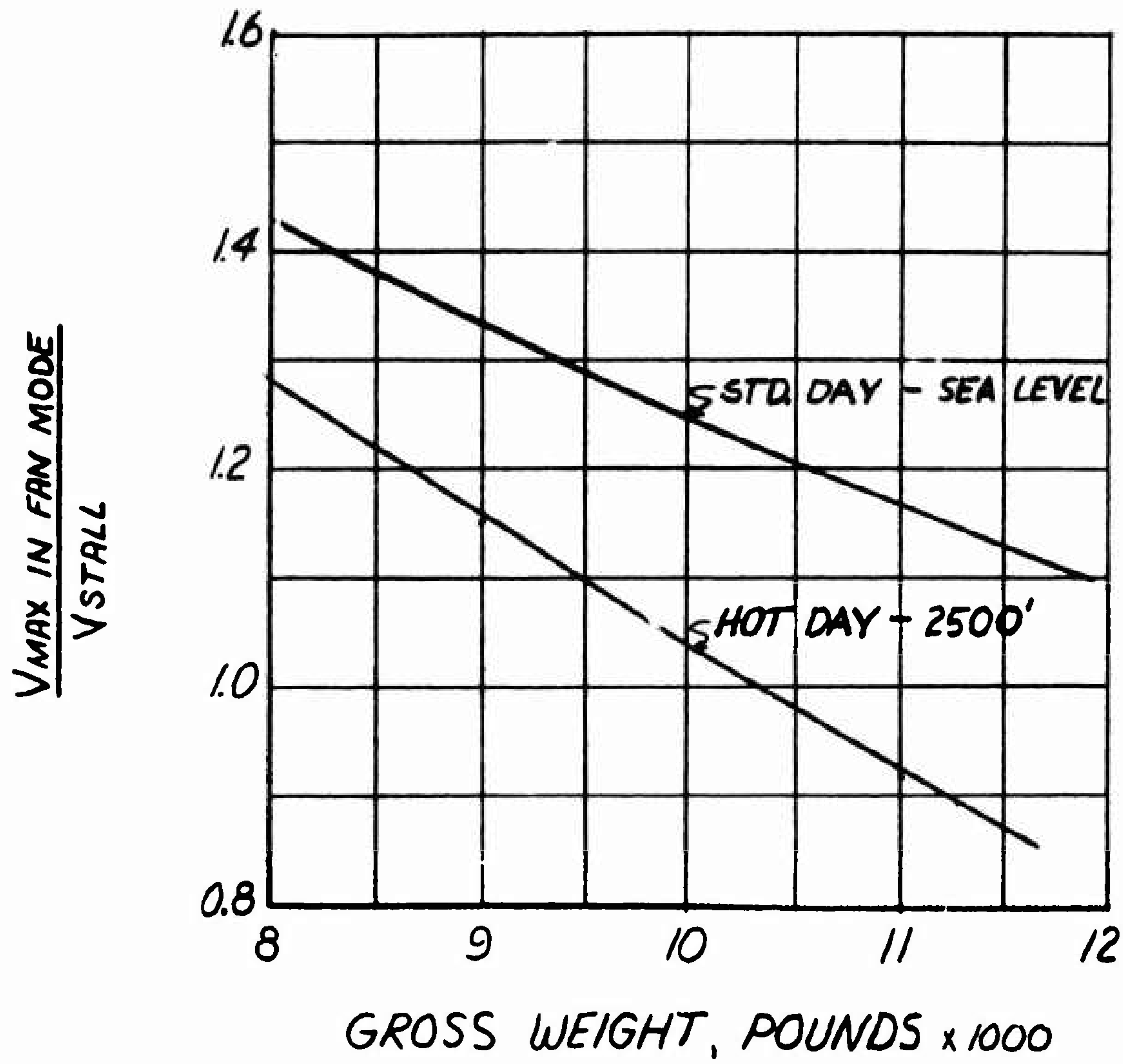

FIG 4